One Arc Degree Core Substructure of the Virgo Cluster

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Abstract. The results of an analysis of the substructure of 1 degree field galaxies of the Virgo cluster by means of the S-tree technique developed by Gurzadyan et al [28-31], are represented. The existence of 3 main subgroups is shown and their dynamical parameters are obtained. The mass centers of the subgroups appear to be aligned in the direction parallel to the elongation of the Virgo cluster. The morphological analysis shows some domination of dwarf galaxies in the subgroup A containing M 87, and existence of two spiral galaxies N4425 and N4461; the latter fact can be crucial for the estimation of the distance of the Virgo cluster by means of the search of Cepheids in that spirals.

1 Introduction

The study of substructures in galaxy clusters is important for the understanding of the evolution of galaxy clusters [1-3], as well as for cosmology [4-7]. Substructures seem to be often observed features in many clusters of galaxies. Various studies (e.g. [8-12]) show that at least 30 - 50 per cent of rich clusters reveal multi-component structure in galaxy distributions and in X-ray images [13-16]. Evidence for the presence of substructures in clusters of galaxies is anticipated also from theoretical studies [17-19]. Some studies have shown that morphological segregation of the galaxies in the cluster possibly has close connection to the cluster substructure [20,21].

Virgo cluster is the nucleus of the Local Supercluster. It is an irregular system. Virgo cluster has a core structure that is centered on M87 [22], and also is known by its complex substructure [23]. The large scale X-ray image of Virgo cluster [24] is very similar to the structure in the galaxy distribution [25,26],

Since Virgo cluster is the nearest large concentration of galaxies, it plays critical role in understanding of the general properties of the individual galaxies in the cluster and its relations with that of the whole system, and large-scale structure of the universe as well. For example, the problem of orientation of spin vectors of galaxies, which is an important tool to probe the epoch of the origin and formation of galaxies and clusters, has been carried out for the Virgo cluster [27].

In the present paper we use S-tree method developed by Gurzadyan, Harutyunyan & Kocharyan [28,29,31]. The method has been already applied for the study of the substructures of the Local Group [32], and Abell [50,51] and Coma clusters [52]: e.g. in the case of the Local Group aside from confirmation of the general picture known from other studies, some new associations between particular galaxies have been observed [32]. The same geometrical approach can be also rather informative while studying the fractal properties of the galaxy distribution [33,34].

The aim of the present study is to reveal the substructures in central - around M87 (N 4486) - one degree field of Virgo cluster. This study is the first step towards the revealing of the Virgo cluster substructure by S-tree code. The number of galaxies in the catalog is being increased essentially with the increase of the field, so that the time required for dealing with the phase space of many dimensional system by S-tree, increases sharply (non-linearly), though, in principle, S-tree has no any constraint on the limiting number of galaxies. We hope to perform the study of larger fields – from 2 up to 6 degrees, as well. Because of the expected robust character of the main conclusions of this preliminary study, as discussed in section 2, we decided to represent them in the present paper.

In section 2 we summarize the basic principles underlying the S-tree technique. In section 3 we describe our subsample of Virgo galaxies and present the results of application of the S-tree method to determine the hierarchical substructure of this sample. Finally, in section 4, we discuss the obtained results, morphology of galaxies, and also identify suitable candidate galaxies for future Cepheid observational programs. This fact can be of particular importance, given the crucial role of the Virgo cluster in calibration of the cosmological distance scale [35], and especially, because of the measurements of the distance of Virgo cluster via NGC 4571 and M100 [35,36] and some other galaxies, aiming the determination of the Hubble constant.

2 The S-Tree Technique

Here we outline the main points of S-tree technique, referring for details to papers [28-30] and to the monograph [31].

S-tree is based on the property of structural stability, well known in the theory of dynamical systems, enabling to reveal the robust properties of the systems based on a limited amount of information. Gravitating systems being exponentially unstable systems, therefore, are relevant for this purpose.

The main motivation of the developing of various new statistical methods here, is the radical difference of the problem of dynamics of clusters of galaxies from the stellar dynamical problem. This difference once more became clear while developing a method of reconstruction of the transversal component of the velocity of clusters of galaxies in [38].

Two main concepts are the basic ones for the S-tree technique: the introduced *degree of boundness* of various members of the system (galaxies), and the corresponding *tree-diagram* to representation of hierarchical substructure of the clusters.

The transition from the degree of correlation to so-called ρ-boundness is realized using the properties of trajectories the systems in $6N$-dimensional phase space, namely by their deviation on given value ρ in a properly defined measure. The problem of the dynamics of the N-body system is thus reduced to the study of the geometrical properties of the phase space, which in accord to methods developed in theory of dynamical systems, can be described via the two-dimensional curvature $K_{\mu\nu}$. The degree of boundness is thus related to the following matrix:

$$D_{ab} = max_{i,j}\{-K_{\mu\nu}, 0\};$$

$$\mu = (a,i), \nu = (b,j); a,b = 1,2,..,N; i,j = 1,2,3.$$

where the tensor K is determined via the Riemannian curvature $R^{\mu}_{\lambda\nu\rho}$ (u is the velocity of geodesics)

$$K^{\mu}_{\nu} = R^{\mu}_{\lambda\nu\rho} u^{\lambda} u^{\rho}$$

of the Riemannian manifold defined by a metric depending on the potential of interaction (see [39]).

The results of the calculations describing the hierarchical substructure of the system are represented by the tree-diagram (*S-tree*) via the corresponding transition to matrices Γ_{ab} from D_{ab}:

$$\Gamma_{ab}(\rho) = \{0\,1\}$$

The input data for the S-tree analysis of a cluster of galaxies are as follows: the 2D coordinates of the galaxies, their redshifts and the magnitudes.

The latter values via the assumption $M = constL^n$, where L denotes the luminosity, M - the mass of the galaxies, are used to involve the information on the masses of the galaxies. The present calculations have been performed for $n = 1$, though the results on the subgrouping and the membership of galaxies have been shown to be robust while moving from $n = 1$ to $n = 1/2$.

The results of the S-tree have been compared with those of wavelet analysis, in particular, for clusters of ESO Key program on nearby Abell clusters survey (ENACS). The parallel analysis of the same cluster data by both methods has revealed the general coincidence of the results in defining of the main physical system of the cluster. However, S-tree enables also to resolve the smaller subsystems, in some cases removing the difficulties associated with physically anomalous parameters of apparent substructures indicated by the wavelet.

An essential point in the context of the present study is in which degree the results of the substructure analysis of the sample based on 1 degree field of the cluster can be modified if the larger areas should be also involved. Numerous studies, both of toy models, as well as of real clusters with artificially cancelled fields have shown the following. Since the method is based on the discovery of correlation between the members (galaxies) of the systems, any found correlation cannot disappear with adding of new areas, unless the information on the previous members is changed drastically. Therefore the added new areas supply new galaxies to the existing subgroups or new correlations could appear as well, without the distortion of the main subgrouping picture. Though some change in the membership can occur, i.e. a galaxy from one subsystem can move to another one. It is natural, since some galaxies could be well attracted almost equally by the two subgroups; typically the number of such galaxies is not large (1-2), moreover they could be predicted by the analysis of the initial (smaller) sample.

Therefore, the found substructure typically should be robust with respect to the increase of the field of consideration. Note only, that for system with larger number of members (or of larger field), the normalization of the degree of boundness is changed, since one deals with different phase spaces. Practically this leads to the possibility of probing more and more deeper structures (i.e. of more strongly correlated ones) with the increase of the number of the members of the system.

3 Sample and Results

We applied the S-tree method to analyze a sample of galaxies lying within 1 degree of NGC 4486, from the compilation of CfA catalogue [40]. Among the 125 listed galaxies within the 1 degree core of the cluster, there are 73 galaxies with measured redshifts, and 66 with measured V-band magnitudes. This sample of 66 galaxies is listed in Table 1, including the galaxy name, its coordinates, apparent V-magnitude and heliocentric radial velocity.

As is mentioned above, the S-tree analysis was performed for various M/L relations, but the results were stable. Therefore here the results for $n = 1$, i.e. with constant mass to luminosity ratio, are shown only. The hierarchical substructure identified by the S-tree analysis indicate that the main group contains 36 galaxies. Remaining 30 galaxies either are chance projections and/or background objects. This group itself consists of three subgroups - denoted A, B, and C and containing 17, 12 and 6 galaxies, respectively. From 17 galaxies of the M 87 subsystem (A), 10 are more strongly bounded than the rest 7. Group A is the group containing M87, which one should then most reasonably associate with the core of the Virgo cluster. The galaxy NGC 4473 does not belong to any of determined groups in the central 1 degree region, though it contributes into the gravitational potential of the whole central region of Virgo cluster. In general, the S-tree results indicate that we deal with fractions of more larger subgroups, especially, in the case of groups B and C, so that the increasing of the field most probably would supply additional galaxies into these groups.

In Figure 1 the projected positions of the 36 galaxies are plotted, indicating via different symbols the galaxies belonging to A, B and C groups. We see that not only the projected positions of these galaxies but also the redshift information only is not enough to specify the subgroups due to some overlapping of their redshift distributions (Figure 2).

Table 2 represents the list of galaxies, members of A, B and C groups within the central 1 degree field of Virgo cluster. In the Table 2 the following information is included: (1) the name of the subgroups: (2) the name of the galaxies, including their relative degree of boundness, s-strong, w-weak, and their radial velocities. For each galaxy the B magnitude, diameter and axial ratio from RC3 [41], the morphology is given according to [42] and position angles (P.A.) from UGC [43]. For those galaxies which are not included in UGC, P.A. are measured by ourselves on red prints of POSS.

Table 1: Galaxies in 1 degree field with messured redshits and magnitudes - 66 objects

Galaxy	RA(1950)	Dec(1950)	mv	V(km s-1)
1223+1226	12 23 56.9	12 26 25	16.60	16364
N4413	12 24 00.0	12 53 00	13.04	96
I3344	12 24 00.0	13 51 00	15.20	1375
I3349	12 24 15.0	12 43 48	15.30	1471
I3355	12 24 18.0	13 27 12	15.20	-9
I3363	12 24 31.2	12 50 06	15.50	791
N4425	12 24 42.0	13 00 42	13.21	1881
N4431	12 24 55.2	12 34 06	14.50	913
1225+1311	12 25 06.0	13 11 00	17.30	28322
N4435	12 25 07.8	13 21 24	12.03	773
N4436	12 25 10.2	12 35 30	14.80	1125
N4438	12 25 13.6	13 17 07	12.00	86
N4440	12 25 21.6	12 34 12	13.09	739
1225+1215	12 25 22.7	12 15 56	17.40	26483
1225+1157	12 25 29.9	11 57 25	17.50	20751
1225+1221	12 25 34.2.	12 21 18	15.85	26777
I794	12 25 37.8	12 22 00	15.10	1934
I3381	12 25 42.0	12 04 00	15.10	637
1225+1324	12 25 42.0	13 24 00	17.60	28636
I3388	12 25 55.8	13 05 54	15.40	1761
N4452	12 26 12.0	12 02 00	13.33	223
I3393	12 26 12.0	13 11 00	15.10	466
N4458	12 26 25.8	13 31 06	13.32	684
N4461	12 26 31.2	13 27 42	12.37	1925
1226+1243	12 26 51.6	12 43 36	15.56	538
1227+1234	12 27 06.0	12 34 00	17.50	26041
N4473	12 27 16.8	13 42 24	11.61	2236
1227+1330	12 27 18.0	13 30 19	17.40	13100
1227+1157	12 27 20.3	11 57 13	16.00	25085
1227+1218	12 27 39.3	12 18 51	16.80	16860
1227+1346	12 27 45.9	13 46 09	17.10	24879
N4478	12 27 46.2	12 36 18	12.57	1370
N4479	12 27 46.8	13 51 12	13.93	858

Table 1: Cont.

Galaxy	RA(1950)	Dec(1950)	mv	V(km s-1)
1227+1244	12 27 49.0	12 44 22	18.50	26000
N4486B	12 28 00.0	12 46 00	14.50	1586
1228+1242	12 28 09.7	12 42 09	21.96	16285
1228+1238	12 28 10.5	12 38 04	16.80	26285
1228+1238	12 28 13.3	12 38 32	16.60	25396
1228+1241	12 28 13.4	12 41 43	21.61	22430
1228+1237	12 28 14.9	12 37 27	21.65	6310
1228+1236	12 28 15.7	12 36 13	21.71	14000
1228+1244	12 28 15.8	12 44 06	21.24	13160
1228+1241	12 28 15.9	12 41 25	20.88	5150
1228+1219	12 28 17.4	12 19 18	17.00	1250
N4486	12 28 17.6	12 40 01	10.30	1292
1228+1244	12 28 18.0	12 44 14	21.11	7000
1228+1242	12 28 19.8	12 42 53	21.24	2925
N4486A	12 28 24.0	12 33 00	11.20	450
1228+1238	12 28 24.5	12 38 58	20.79	2735
1228+1238A	12 28 28.5	12 38 21	20.73	80320
1228+1246	12 28 37.0	12 46 10	20.86	11095
I3443	12 28 44.4	12 36 30	15.60	1814
I3457	12 29 19.6	12 55 57	15.40	1469
I3459	12 29 22.8	12 27 00	15.50	278
I3466	12 29 33.0	12 05 36	15.30	786
N4506	12 29 42.0	13 42 00	14.20	681
I3461	12 29 51.0	12 10 12	15.50	1110
I3467	12 29 52.2	12 03 48	15.40	7519
1229+1204	12 29 54.0	12 04 00	15.40	7810
I3475	12 30 04.8	13 03 00	14.94	2572
I3489	12 30 42.0	12 31 00	15.20	7834
I3492	12 30 42.0	13 08 00	15.60	2004
I3492A	12 30 48.0	13 08 00	15.30	-571
I3501	12 31 18.0	13 36 00	15.00	1608
N4531	12 31 42.0	13 21 00	13.30	8
I3509	12 31 48.0	12 21 00	15.30	2073

Table 2: Members of A, B and C Groups Within the Central 1 Degree Field of the Virgo Cluster

Group	Galaxy	B(T)	Morph	PA
Aw	N4425	12.82	SBa	27
As	I3344	14.80	dE6	54
As	I3349	14.78	dE1	43
Aw	I3388	15.31	dE5	101
Aw	I794	14.73	dE3	110
As	N4436	14.03	dE6/dS	118
Aw	N4461	12.09	Sa	9
As	N4478	12.15	E2	140
As	N4486	9.58	E0	-
As	1228+1219	16.80	BCD	152
As	N4486B	15.11	E1	63
Aw	I3443	15.64	dE0	-
As	I3457	15.40	dE3	47
As	I3461	14.82	dE2	30
Aw	3492	14.58	E3/S0	116
Aw	I3509	14.73	E4	121
As	I3501	14.50	dE1	-
B	N4413	13.97	SBbc	60
B	I3355	14.82	SBm	172
B	N4438	10.90	SB	27
B	N4452	13.30	S0	32
B	I3459	14.62	dSB0	-
B	N4531	12.58	Sa pec	155
C	I3363	15.40	dE7	127
C	N4431	13.72	dS0	177
C	N4435	11.84	SB0	13
C	N4440	12.74	SBa	94
C	I3381	14.95	dE4	110
C	1226+1243	15.56	dE1	14
C	N4458	12.92	E1	46
C	I3393	14.60	dE7	47
C	N4479	13.45	SB0	-
C	N4486A	13.40	E2	170
C	I3466	15.72	pec, N	29
C	N4506	13.64	S pec	110
MS	N4473	11.10	E5	100

Table 3:

Subgroup	N	V (km/s)	σ(km/s)
A (core)	10	1366	174
A	17	1473	480
B	6	113	115
C	12	693	148

4 Discussion

4.1 The membership of galaxies in groups

The galaxies of our sample lie in the region of Virgo cluster [44]. which has average heliocentric velocity 991 km/s and velocity dispersion 661 km/s. The dynamical characteristics of the Virgo 1d field subgroups A, B and C are given in Table 3, including the average redshifts (V) and the velocity dispersions (σ); the results for the 17 galaxies of subgroup A and for its core of 10 galaxies are given separately.

4.2 Spatial distribution of substructures

Already the visual inspection of Figure 2 gives an impression that A, B and C subgroups of galaxies in the center of Virgo cluster have collinear distribution. In order to quantify this impression, we have determined the coordinates of their mass centers:

$$A:\ \alpha_1 = 12^h 28^m 55.83^s;\ \delta_1 = 12^d 30^m 16.196^s$$

$$B:\ \alpha_2 = 12^h 25^m 31.00^s;\ \delta_2 = 12^d 32^m 53.710^s$$

$$C:\ \alpha_3 = 12^h 27^m 15.61^s;\ \delta_3 = 12^d 32^m 50.110^s$$

To test their alignment we use the equation:

$$\tan(\delta_1)\sin(\alpha_3 - \alpha_2) + \tan(\delta_2)\ \sin(\alpha_3 - \alpha_1) + \tan(\delta_3)\sin(\alpha_1 - \alpha_2) = 0,$$

i.e. the equation of the three points (α_i, β_i) situated on a line. Our computations yield for the left hand side 0.01, i.e. the mass centers of A, B and C groups are well aligned.

The collinear distribution of the substructures in the centre of the Virgo cluster is not a unique one. According to [16] there is a tendency for alignment in the substructures in clusters. The position angle of the line connecting A, B and C subgroups is 92°. According to [45] the P.A. angle of

Table 4:

Subgroup	P.A.	d (kpc)	D(kpc)
A (core)	98	90	1200
A	92	6	80
B	172	63	600

the jet of M 87 is $290^{\circ}.80 \pm 0.5$, while the P.A. of major axis of the Virgo S cluster is about 100°.

The revealed three subgroups also show some elongation. In the Table 4 we represent the P.A. of the major axes of A, B and C, the projected distance of their major axes from their mass centers (d) and the major diameter of each subgroup. Note that, the major axes of A and B are almost parallel to the direction of alignment of subgroups, while the major axes of C is almost perpendicular to it.

We had looked also for the angular distribution of the galaxies within each subgroup. The formula [45]

$$N(\theta) = \mu[1 + \Delta_1 \cos(2\theta_i) + \Delta_2 \sin(2\theta_i)],$$

where

$$\Delta_1 = [\Sigma N(\theta) \cos(2\theta_i)]/3\mu; \Delta_2 = [\Sigma N(\theta) \sin(2\theta_i)]/3\mu;$$

has been used; $N(\theta_i)$ is the number of galaxies with position angle in i-th binning, μ is the mean surface density of galaxies. This formula yields $\Delta_{1,2} = 0.1 - 0.9$, thus indicating no any significant departure from the homogeneous distribution. This is not surprising given the small number of galaxies in the samples.

4.3 Morphology of Galaxies in Subgroups

In the Table 5 data for galaxies morphological distribution in the A, B and C groups are presented. Morphological types are sampled as ellipticals (E), spirals (S), lenticulars (S0) and dwarfs (dE, dS0 and BCD galaxies). Some remarkable features can be noticed. One concerns, for example, the population of dwarf galaxies in the subgroup A; seven from ten of those galaxies are located in projection within 90 degrees with respect to the direction of the jet of M 87. The same subgroup contains also two spirals N4425 and N4461. Subgroup B is dominated with spirals, with no ellipticals. Dwarf galaxies are the majority also in group C. Though one should be cautious in

Table 5:

Subgroup	E	S0	S	Dwarfs
A	5		2	10
A (core)	3		2	2
A	3			7
B		1	4	1
C	2	2	2	6

drawing any far going conclusions from these morphological distributions, and moreover, these results have no reason to coincide with the populations in clusters, nevertheless, note, that the E/SO/S ratio is different than what is known for clusters of various richness [20].

4.4 Cepheids and the Virgo Distance Problem

The existence of the two spiral galaxies in the subgroups A, i.e. the one including the M 87, revealed by the present study can provide possibility for the estimation of their distances by means of the search of Cepheids in those spirals. This fact can be crucial for the estimation of the Hubble constant [46-49].

5 Conclusions

The present study enables us to draw the following main conclusions:

(a) Three main subgroups are revealed by means of the study of 1 arc degree central field of the Virgo cluster;

(b) The dynamical parameters of the 3 subgroups are estimated. Alignment of the mass centers of the subgroups correlates with the elongation of the Virgo cluster.

(3) The subgroups themselves show some elongation in projection, so that the elongation of the subgroups A and B is parallel to the the alignment of the subgroups, and is perpendicular to that of the subgroup C.

(4) The subgroup A is dominated by dwarf galaxies, with some preference in their location in the direction of the jet of M87. No ellipticals exist in the subgroup B.

(5) The presence of two spirals N4425 and N4461 in the subgroup A can provide possibility for the estimation of the distance to the core of the Virgo

cluster via Cepheids.

The studies of the larger fields of the Virgo cluster will be desirable for the evaluation of the physical content of these conclusions, as well as for the general aim of the understanding of the role of subgroups in the dynamics of clusters of galaxies [50-52].

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Figure Captions.

Figure 1. The distribution of galaxies in 1 arc degree field of Virgo cluster. Triangles denote the galaxies of subgroup A, crosses - of subgroup B, diamonds - of subgroup C.

Figure 2. The redshift histrograms of the subgroups; the notations are the same as in Figure 1.